Developing and evaluating algorithms for lateral erosion of bedrock channels in landscape evolution models

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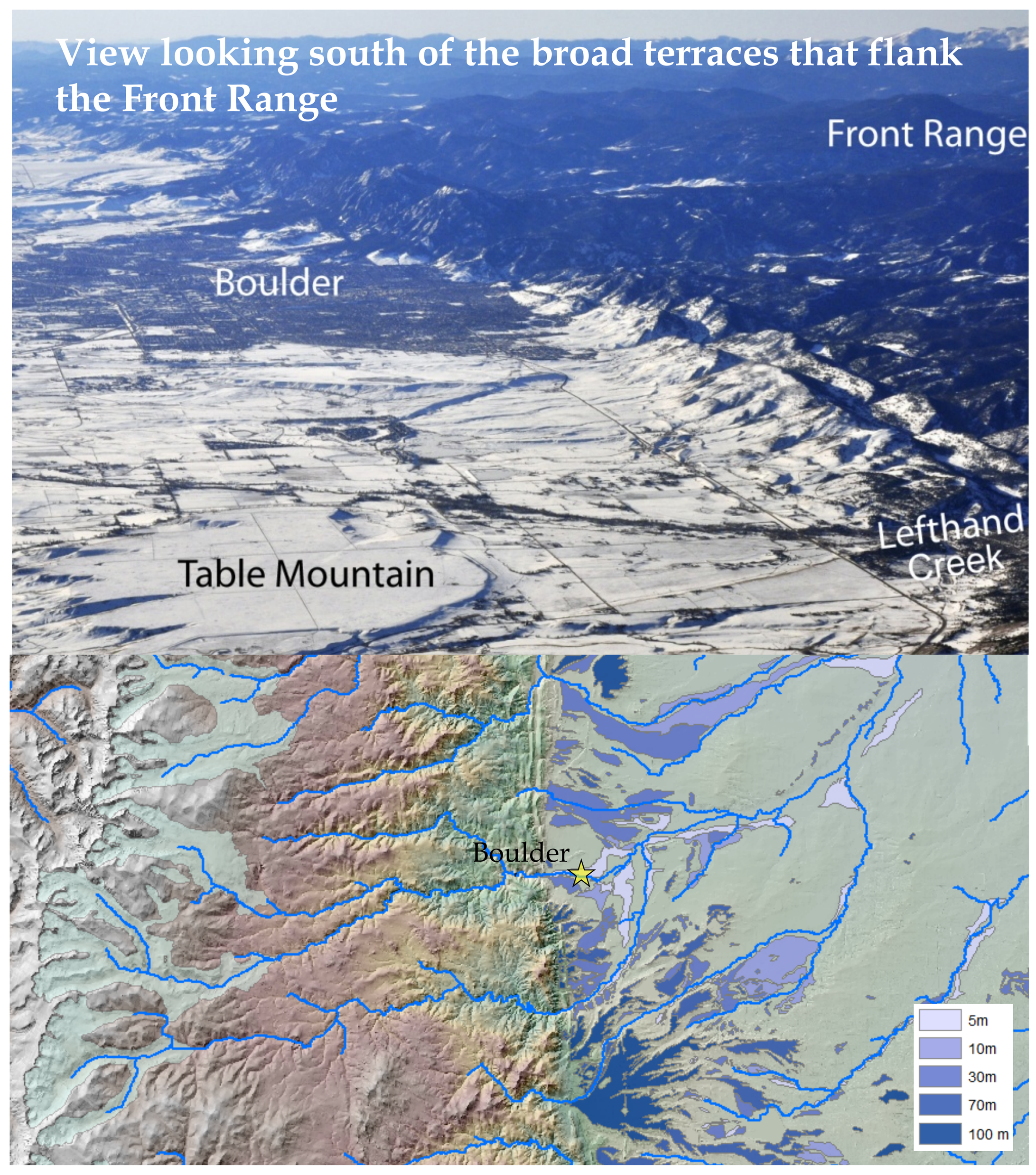
Introduction and Motivation

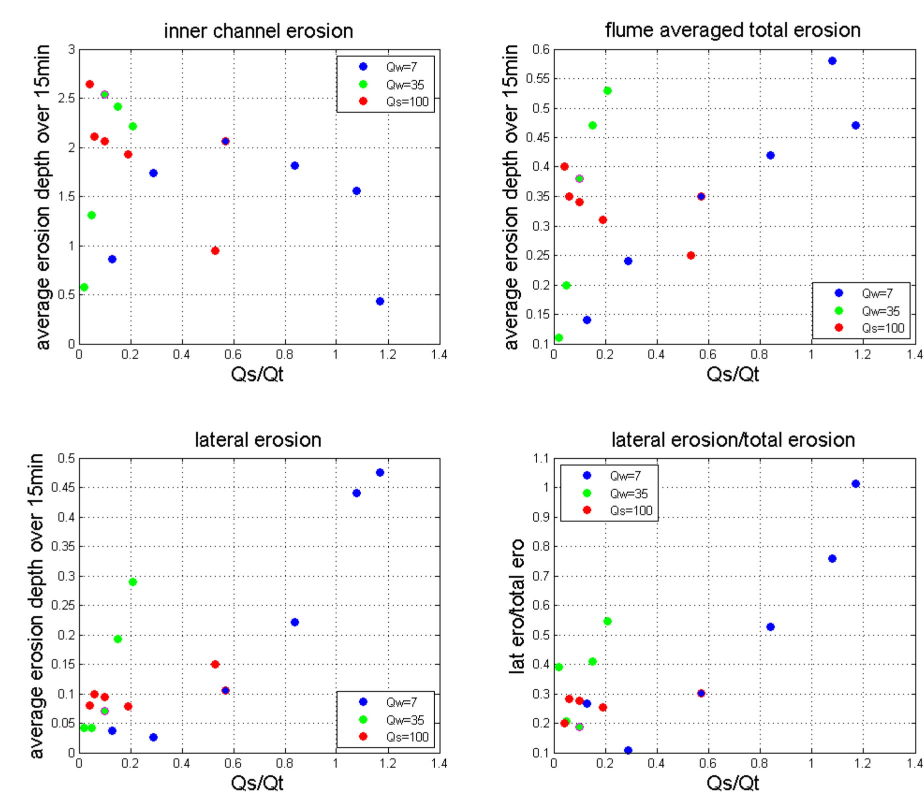
Theory for the vertical incision of bedrock channels is well established and is widely implemented in our current generation of landscape evolution models. However, existing models in general do not seek to implement rules for lateral migration of bedrock channel walls. This is problematic, as geomorphic problems such as terrace formation and hillslope-channel coupling depend heavily on accurate simulation of valley widening. We have begun to develop and implement a theory to represent the lateral migration of bedrock channel walls in a landscape evolution model. In a real channel, rates of lateral channel wall erosion depend on the shear stress directed at the channel walls and the resisting strength of the bedrock. Shear stress directed at the channel walls is a function of channel curvature, discharge magnitude, and sediment supply, which provides tools to abrade the walls and cover to shield the bed from erosion. Applying empirically based simple rules for lateral erosion in a gridded model results in wider valleys and more dynamic stream networks, especially in landscapes with weak bedrock. To our knowledge, these efforts represent the first attempt to incorporate lateral erosion in a network-based landscape evolution model.



The hillshade map above of the Front Range and plains shows 5 levels of broad strath terraces, which are present in large, previously glaciated catchments, as well as catchments with no evidence of past glaciation.

Lateral Erosion Theory

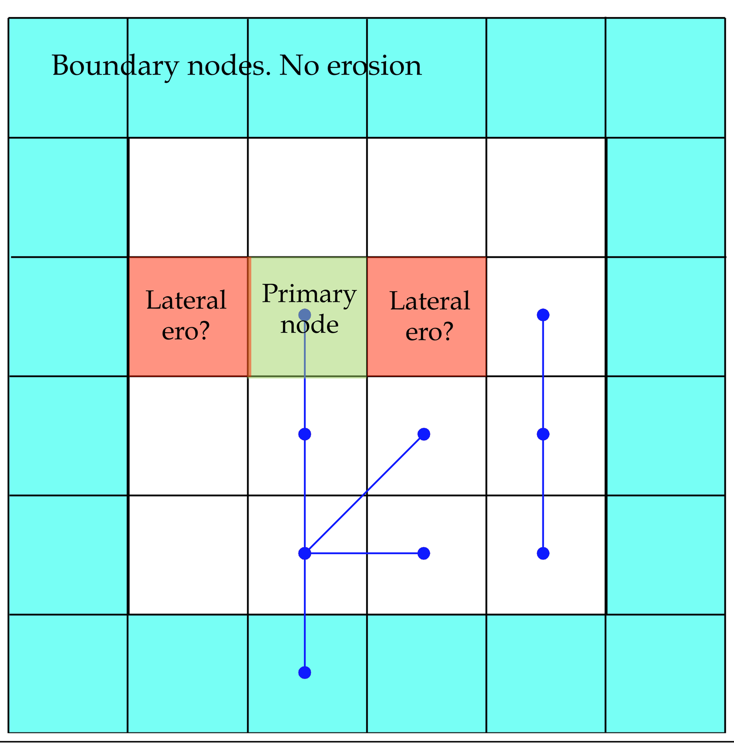
We used previously published experimental data (Johnson and Whipple, JGR, 2010) showing the influence of sediment flux and discharge on bedrock channel incision to determine the relationship between rates of lateral erosion and sediment flux and discharge. These data indicate a linear relationship between increasing sediment flux and bed cover and increasing lateral erosion.



After Johnson and Whipple 2010

Model Algorithm

We use the Landlab modeling environment to abstract these rules for lateral erosion of channel walls to a landscape evolution model.



- Calculate dz/dt at each node (Davy and Lague, 2009)
- Calculate Qs/Qt at each node
- Determine which lateral neighboring node gets eroded (figure to left)
- Determine whether lateral erosion occurs: if Qs/Qt is larger than a randomly drawn number between 0 and 1, neighboring cell gets all of the erosion of the primary cell (figure to left)
- Calculate stable time step size
- Erode landscape

Land surface elevation:

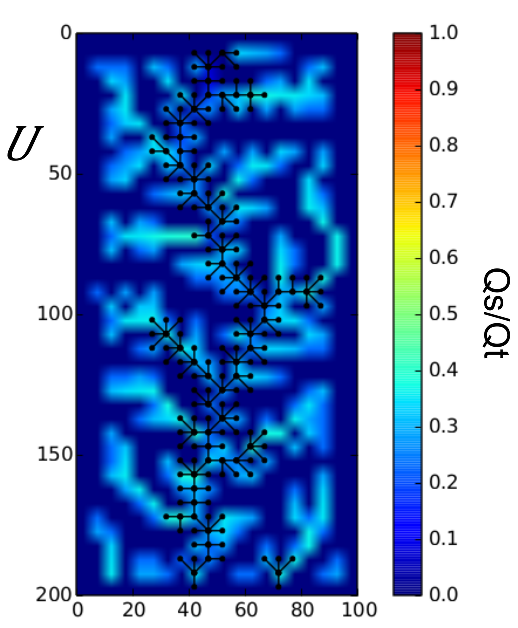
$$dz/dt = \alpha Q_s/A - K A^{1/2} S + U$$

Transport-limited (α >1)/ detachment-limited (α <1) dimensionless number:

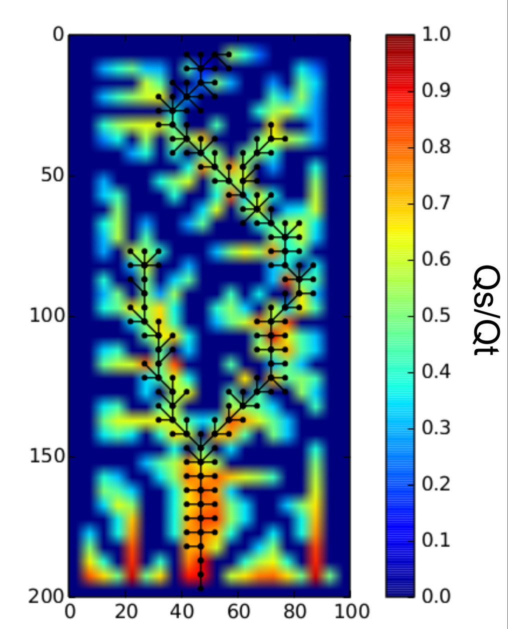
$$\alpha = \frac{v_s}{d_* / R}$$

Transport capacity:

$$Q_t = K A^{3/2} S/\alpha$$



Model run K=1e-4, alpha = 0.6

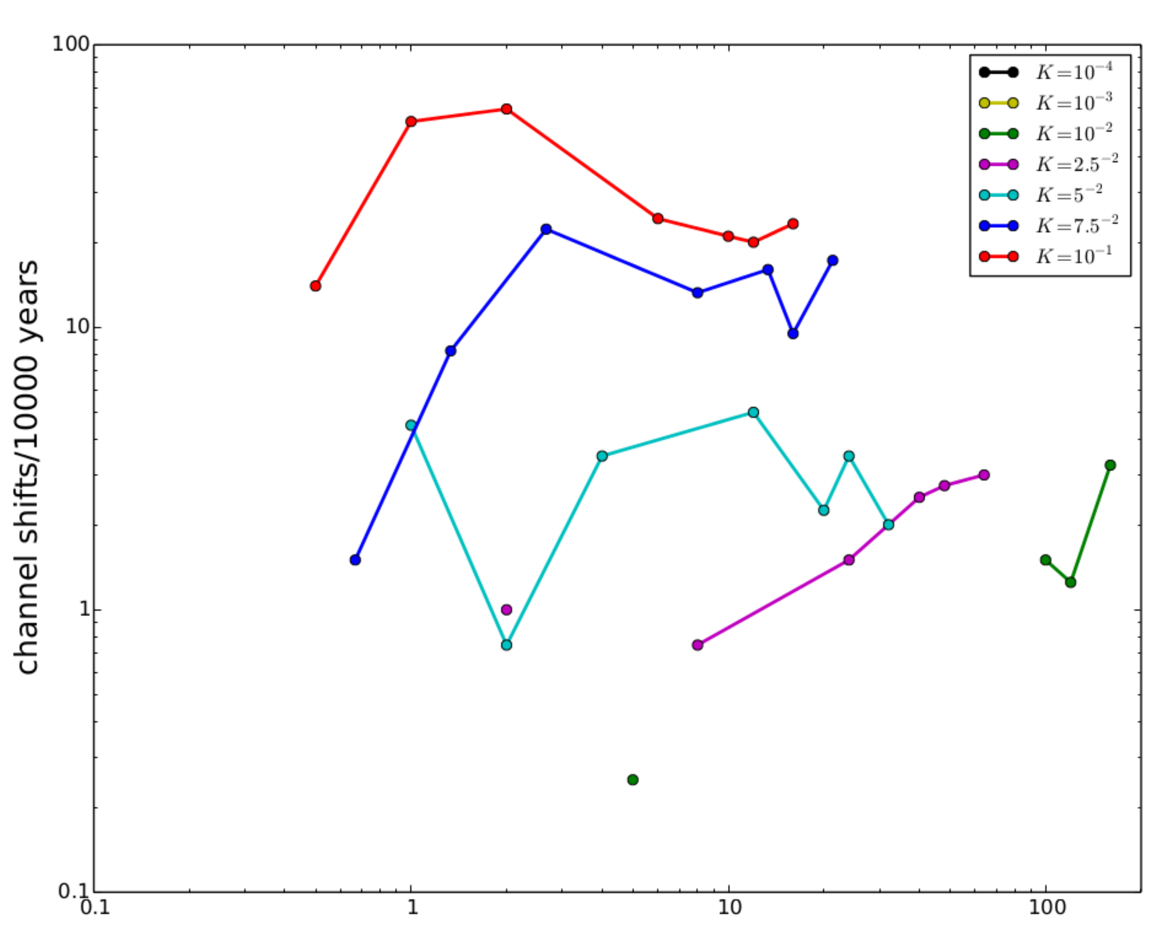


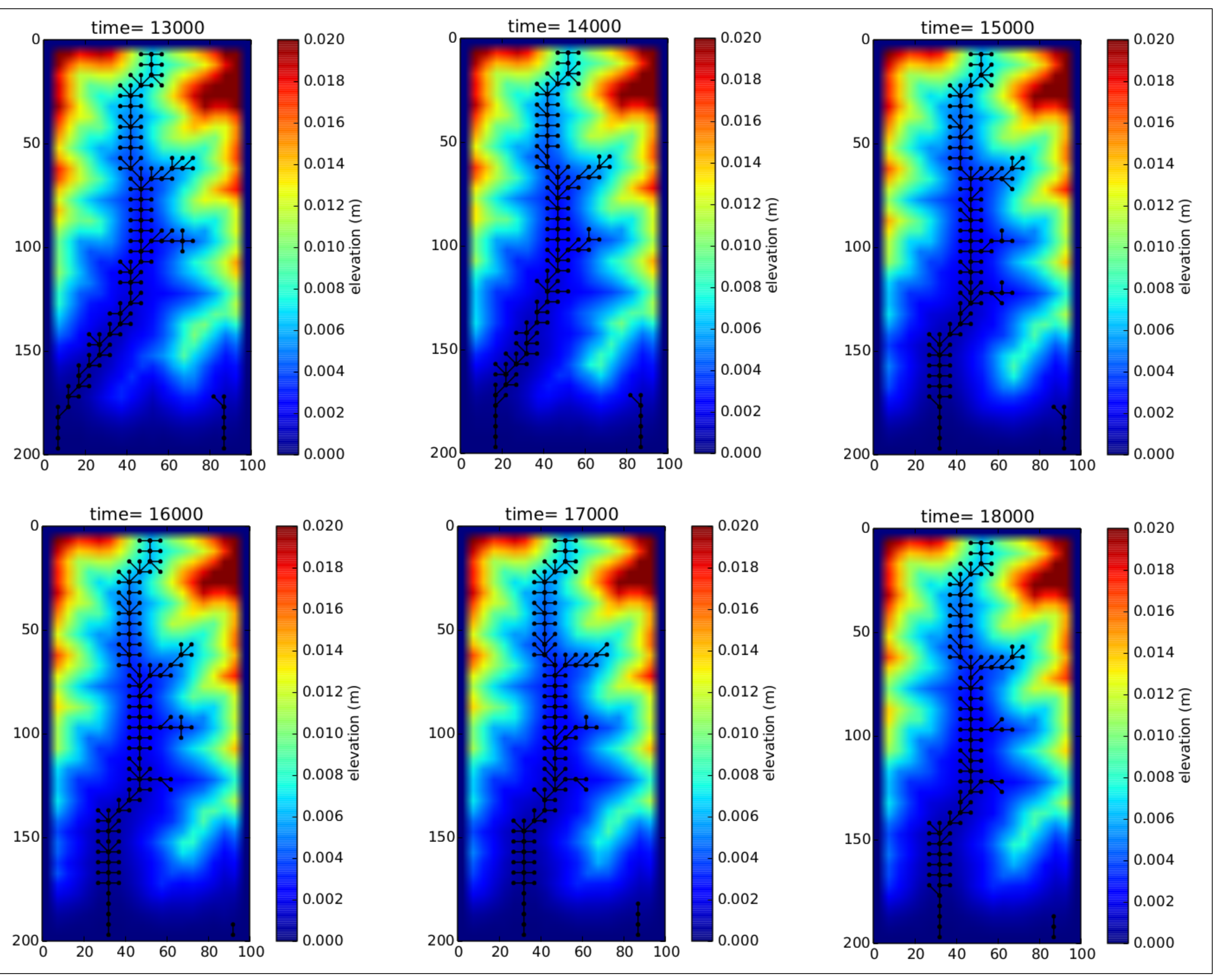
Model run K=5e-2, alpha = 0.6

The figures above show Qs/Qt distribution over the model domain for two model runs. Higher values of Qs/Qt at a node results in a greater chance of lateral erosion of neighboring nodes.

The series of figures to the right shows the lateral migration of a stream over 6000 years after the model has reached steady state. In this model K=0.1, alpha = 1. The stream is indicated by the black lines. The stream sweeps over the lower half of the model domain, smoothing the topography and creating a wide bedrock valley

The figure below shows results from 49 model runs with a range of K values (1e-4 to 1e-1) and alpha values (0.05-1.6). The figure shows the maximum number of times the main channel in the models shifted by at least 1 cell in 10,000 years of model time vs. the ratio of alpha/K





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References: Johnson, J.P.L. and Whipple, K.X. (2010), Evaluating the controls of shear stress, sediment supply, alluvial cover, and channel morphology on experimental bedrock incision rate. JGR, 115, F02018.
Davy, P. and Lague, D. (2009), Fluvial erosion/transport equation of landscape evolution models revisited. JGR, 114, F03007.